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THE FORMATION OF LEUCITE IN IGNEOUS ROCKS

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INTRODUCTION

In the following pages are presented the results of an attempt at the determination of the chemical characters of magmas which may control the formation of leucite in igneous rocks. Connected with this is an examination of the validity of the orders of affinity of the bases for silica and for alumina, which have been assumed as fundamental in the calculation of the norm in the quantitative classification. The paper is an extension of some previous studies, to be referred to subsequently, undertaken under the auspices of the Carnegie Institution. It may be pointed out here that the methods employed in the case of leucite are capable of application to other minerals.

I must express my deep obligations to my friends, Dr. Cross and Professor Iddings, with whom the first draft of this paper was discussed, for valuable suggestions in regard to the plotting of the diagrams and other matters, by which the work has gained much in simplicity and, it is to be hoped, in intelligibility.

It is commonly assumed or explicitly stated that the rocks in which leucite occurs are usually low in silica and high in alkalies, especially potash. But no definite limits for silica or for potash have been established, and leucite-bearing rocks are known which are quite high in silica and low in potash. Over forty years ago Roth[1] pointed out that the silica percentage of the rock could be either above or below that of leucite. Roth, in the last-cited work, and subsequently Zirkel,[2] observe that quartz does not occur with leucite, and the latter speaks of this as one of the few laws which can as yet be enunciated in regard to the mineral associations in igneous rocks. He also notes the fact that leucite occurs more often in association with plagioclase than with orthoclase.

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[1] J. Roth, *Zeitschrift der deutschen geologischen Gesellschaft*, Vol. XVI (1864), p. 690; and also *Beiträge zur Petrographie der plutonischen Gesteine* (1869), p. 90.

[2] F. Zirkel, *Lehrbuch* (1893), Vol. I, p. 646.

The characteristic occurrence of leucite in effusive rocks, and its absence from intrusive ones, have long been known, though recent observations have shown some undoubted exceptions to this latter statement. This general association is commonly attributed to the greater pressure under which the intrusive rocks have consolidated, and also in part to the presence of mineralizers, under which conditions leucite does not seem to be stable.[1] The possibility of potash entering the biotite molecule in combination with magnesia and ferrous oxide under certain circumstances, while under others this complex molecule does not form, but its constituents crystallize as leucite and olivine, has been pointed out and discussed by Lemberg,[2] Bäckström,[3] and others.

The general relations between the occurrence of leucite and the chemical characters of the rocks have been discussed by the authors mentioned above, as well as by others, among whom may be mentioned Iddings[4] and Lacroix.[5] These earlier discussions were largely qualitative, but in a more recent paper[6] Iddings discusses the chemico-mineral relationships of rocks from a mathematical standpoint, illustrated by diagrams, and much of the subsequent discussion is closely analogous to his. In these papers of Iddings the theoretical limits of some ideal magmas are pointed out, and the relationships of actual rocks to them are considered. Still more recently[7] Michel Lévy discusses mathematically the limits of the various magmatic divisions of the quantitative classification, with application to certain rocks, but without discussion of leucite.

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[1] Cf. J. Lemberg, *Zeitschrift der deutschen geologischen Gesellschaft*, Vol. XL (1888), p. 635.

[2] J. Lemberg, *loc. cit.*, p. 636.

[3] H. Bäckström, *Geologiska Föreningens Förhandlingar*, Vol. XVIII (1896) p. 155.

[4] J. P. Iddings, *Bulletin of the Philosophical Society of Washington*, Vol. XII (1892), pp. 166, 176.

[5] A. Lacroix, *Enclaves des roches* (Macon, 1893), p. 637.

[6] J. P. Iddings, *Journal of Geology*, Vol. VI (1898), p. 219.

[7] Michel Lévy, *Bulletin de la Carte géologique de la France*, No. 92 (1903).

In a paper on the rocks of the central Italian volcanoes[1] the relationships of the leucitic and non-leucitic rocks, and the chemical characters of their respective magmas, were discussed with the view of throwing light on the chemical characters which controlled the formation of leucite in this region. Some general conclusions were reached, which will be referred to subsequently, and some of which seem to be of wider applicability. The present paper, as was mentioned above, is an extension of this study, the field being enlarged to include all known leucitic rocks. The theoretical limitations of leucitic norms are first determined mathematically on the basis of certain assumptions, and these are afterward compared with the actual facts as revealed by a study of the rocks themselves.

A great deal of work has been done in recent years by Morozewicz, Vogt, Doelter and his pupils, Day and Allen, and others, in determining the physico-chemical conditions involved in the formation of many of the rock minerals. While this work is of great value and importance, and highly suggestive in many ways, little reference will be made to it in the present paper, in which the more essentially chemical factors will be the main subject of investigation. This is partly because such an extension of the scope of our inquiry would unduly lengthen the paper, and partly because it is felt that such physico-chemical investigations, are not yet so complete and so detailed, especially as regards leucite, as to make their introduction, and the conclusions to be derived from them, satisfactory. They may and will be invoked in the future for the explanation of many of the facts set forth in the subsequent pages, but such an application here seems to be unjustified and rendered merely tentative by the paucity of our knowledge at the present time.

THEORETICAL DISCUSSION

While it is now well recognized that a given magma solidifying under different physical conditions may form very diverse mineral combinations, within the limits imposed by the chemical composition, yet for any given set of physical conditions it would seem that the relative affinities of the chemical constituents of the magma for each other should determine the minerals actually formed. In accordance with the general facts of chemistry these relative affinities would vary more or less with differences in the physical conditions, such as temperature and pressure, and their influence may conceivably be altered by such factors as mass-action or the presence of catalyzers, bringing about different reactions between the constituents of the magma and the consequent formation of different minerals. But for igneous magmas in general, and within the comparatively narrow range of temperatures between the points where crystallization begins and the mass becomes solid, it will be permissible to assume certain general orders of affinity which should control in the great majority of cases, at least, and which a study of the minerals formed in holocrystalline igneous rocks would reveal to us.

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[1] H. S. Washington, "The Roman Comagmatic Region," *Carnegie Publication* No. 57 (1906), p. 181.

Leaving out of account all of the (usually) minor chemical constituents, for the sake of simplifying the discussion, we may assume that rock magmas are composed of the oxides: silica, alumina, ferric oxide, ferrous oxide, magnesia, lime, soda, and potash. Whether these exist as such in the magma before solidification, or whether they are combined into more complex molecules, is an unsettled question, and one which need not concern us here. It is evident that a study of the relative affinities of each of these for the others would be very complex, but our knowledge of igneous rocks and of their component minerals clearly indicates that certain ones are of especial importance.

Of these the most important, and the one which most interests us, is that of the bases for silica, as silica is always present in the largest amount, and the great majority and the most abundant of the igneous rock minerals are silicates. While no universally applicable order of affinity can be established, for reasons given above, yet the well-known facts of mineralogy and the experimental researches of Lagorio, Morozewicz, and others, indicate the following as being the one which controls in the great majority of cases,[1] and the one which we may assume as fundamental in the present investigation. Beginning with the oxide which has the greatest affinity for silica, this order is: potash, soda, lime, magnesia, and ferrous oxide. A second order of affinity of almost equal importance is that of the bases for alumina, usually the next most abundant constituent after silica. This order is the same as that for silica. Upon these are based very largely the calculation of the norm in the quantitative system of classification, that is, the simplest expression of the mineral molecules which experience has shown are most likely to be formed in igneous rocks.

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[1] Cf. Cross, Iddings, Pirsson, and Washington, *Quantitative Classification of Igneous Rocks* (Chicago, 1903), p. 192.

On these assumptions the most important mineral molecules formed in the norm by each of the above five oxides may be referred to two pairs for each one, diopside being considered as split up into simpler molecules, and kaliophilite being disregarded on account of its excessive rarity. These pairs, one member of which has the highest and the other the lowest amount of silica, are as follows:

	Molecule	Base to Silica	Molecule	Base to Silica
Salic	Orthoclase, $KAlSi_3O_8$	1 : 6	Leucite, $KAlSi_2O_6$	1 : 4
	Albite, $NaAlSi_3O_8$	1 : 6	Nephelite, $NaAlSiO_4$	1 : 2
	Anorthite, $CaAl_2Si_2O_8$	1 : 2	Wanting	
Femic	Wollastonite, $CaSiO_3$	1 : 1	Akermanite, $Ca_4Si_3O_{10}$	4 : 3
	Enstatite, $MgSiO_3$	1 : 1	Forsterite, Mg_2SiO_4	2 : 1
	Ferrosilite,[1] $FeSiO_3$	1 : 1	Fayalite, Fe_2SiO_4	2 : 1
	Magnetite, Fe_3O_4	1 : 0		

Considering holocrystalline rocks alone, in accordance with these assumed orders of affinity of the bases for silica and for alumina, quartz would be formed only when there is an excess of silica over that needed to permit the existence of the higher silicated pair for each base present, when the lower silicated member would be absent. If there is insufficient silica for this, the potash will form orthoclase rather than leucite, the magnesia and ferrous oxide forming olivine rather than hypersthene, and soda forming nephelite rather than albite if necessary. On the basis of the assumed order of affinity for silica, melilite should be formed rather than nephelite; but it is found that this is not the case, melilite being notoriously much more rare than nephelite. This undeniable exception may be attributed (in great part at least) to the mass-action and the high stability of the complex pyroxene molecules, into which lime enters in preference to melilite. After the potash is satisfied, the soda would form albite rather than nephelite, if there is silica enough, the magnesia and ferrous oxide remaining in olivine. Leucite should thus be formed only when there is insufficient silica for all of the potash to form orthoclase, even after all of the soda, magnesia, and ferrous oxide have been reduced to their lowest silicated conditions.[1] These relations are somewhat complicated by the presence of the diopside, magnetite, ilmenite, and other molecules; but, as they have been fully discussed elsewhere, further details are uncalled for.

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[1] Cf. Washington, *Professional Paper*, U. S. Geological Survey, No. 14 (1903), p. 90.

The above-described behavior of the various oxides is the *normative* one; that is, the ideal result of the application of the assumed orders of affinity of the bases for silica and for alumina. It remains to be seen whether it is the *normal*[2] one or not; that is, whether the actual facts are in accordance with these assumptions, as regards the occurrence of leucite.

In this theoretical discussion we shall first consider the norms only, not the actual rocks, and we shall assume that there is neither an excess of alumina over the alkalies and lime (resulting in normative corundum), nor of alkalies over alumina (resulting in normative acmite or alkali metasilicates), so that alumina may be eliminated from consideration, as well as corundum, acmite, and alkali metasilicates. The possibility of the formation of kaliophilite will be disregarded, as well as the presence of such usually minor constituents as Cl, SO_3, TiO_2, P_2O_5, etc. The numerical relations of the various oxides will be expressed in the following pages as molecular ratios, so as to make them comparable chemically.

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[1] It may be noted that, were the direction of affinity reversed, so that silica had an affinity for the bases, rather than the bases for silica, in the order named, the presumptive order of formation of the minerals would be the reverse of that described. On such a basis we would expect leucite to be formed in preference to orthoclase, then nephelite rather than albite, and hypersthene rather than olivine. On this assumption, therefore, leucite, nephelite, and hypersthene rocks should be more common than olivine ones, which is not the case, and leucitic and nephelitic rocks much more abundant relatively to feldspathic ones than these are known to be.

[2] On page 2 of the paper cited above Michel Lévy apparently considers that the term "normative" is synonymous with "normal," and he objects to it on the ground that the normative minerals are seldom normal ones. He has evidently overlooked our express statement of the distinction between the two words: "normative" being employed by us in the accepted English sense of "establishing or setting up a norm," while "normal" is recognized as having the meaning of "usual" or "common," and is therefore not used in this connection. (Cf. *Quantitative Classification* [1903], p. 147.)

The first problem before us, then, is the determination of the limits of variation in composition of all norms in which leucite does or does not occur in accordance with the principles laid down, and in holocrystalline rocks derived from which modal leucite should or should not be found. This problem is capable of exact mathematical statement and graphic expression.

As the simplest case we should consider first only the persalic, peralkalic, and perpotassic magmas—that is, those composed only of silica, alumina, and potash, the last two present in equal amount—so that the norms of these and holocrystalline rocks resulting from their consolidation would be composed either of quartz alone, quartz and orthoclase, orthoclase alone, orthoclase and leucite, or leucite alone. Such rocks are seldom met with, and their relations would be very simple. Furthermore, they form a limiting value of the next group to be discussed, so they will be dealt with later.

As the next simplest case we may assume that soda is present also in variable amount, the magmas being persalic and peralkalic, but the relations of the alkalies varying from perpotassic to persodic. On our assumption that potash has a greater affinity for silica than has soda, albite and leucite could not be present together in the norms, but these and the holocrystalline rocks derived from such magmas would be composed of quartz, orthoclase, albite, leucite, and nephelite, either alone or in all possible combinations, with the exception just stated. The general chemical composition of such magmas will be represented by the following equations:

$$a\mathrm{SiO_2}+b\mathrm{Al_2O_3}+c\mathrm{Na_2O}+d\mathrm{K_2O}=100$$
$$\mathrm{Al_2O_3}=\mathrm{Na_2O}+\mathrm{K_2O}$$

The variables here are the absolute amounts or percentages of silica, soda, and potash, and the ratios of silica to soda, silica to potash, and soda to potash. Any two of these may be selected as a basis for plotting, and in my paper on the rocks of the Roman comagmatic region the percentage of silica was used for the abscissas, and the ratio $\frac{\mathrm{SiO_2}}{\mathrm{K_2O}}$ for the ordinates. Indeed, all the data represented on Plates I and II have been plotted on these bases, Plate III being the equivalent, thus plotted, of Plate I, as will be discussed later.

This use of ratios which may vary from zero to infinity, however, leads to hyperbolic curves, complicating the relationships and introducing very serious and misleading distortion through the extension of the diagram to infinity in one direction, and is therefore disadvantageous.[1] Consequently, and at the suggestion of Dr. Cross and Professor Iddings, this basis of plotting has been abandoned, and the percentage of silica used for the abscissas and the percentage of potash for the ordinates, both being expressed molecularly. While the relation of silica to potash, an important factor in the question of the formation of leucite, is thus rendered not quite so evident, yet the diagrams gain in simplicity and intelligibility, and there is also the great advantage of dealing only with straight lines, thus immensely simplifying the calculations and the construction, as well as the comparison of the actual rocks with the theoretical data.

The calculation of any given magma is readily carried out by means of the equations already employed for the calculation of the center-points.[2] The results will be given in Table I at the end of this paper. Plotting these data for our assumed peralkalic and persalic magmas, with variable amounts of soda and potash, we obtain the results shown in Plate I. In this the solid lines are those passing through magmatic center-points, and the broken ones those passing through the border-points of the magmatic divisions. The purely sodic magmas lie along the bottom of the diagram, while the purely potassic ones are at the top. One hundred per cent of silica is at the left and zero at the right, as this is in accordance with the diagrams of Iddings and facilitates comparison with them. Furthermore, this corresponds with the order in which the various divisions are arranged in the *Quantitative Classification.*

It will be observed that these lines resemble those of Iddings[3] in some respects. The latter, however, employs for the ordinates the ratio $\frac{K_2O+Na_2O}{SiO_2}$, instead of the percentage of potash, and conse-

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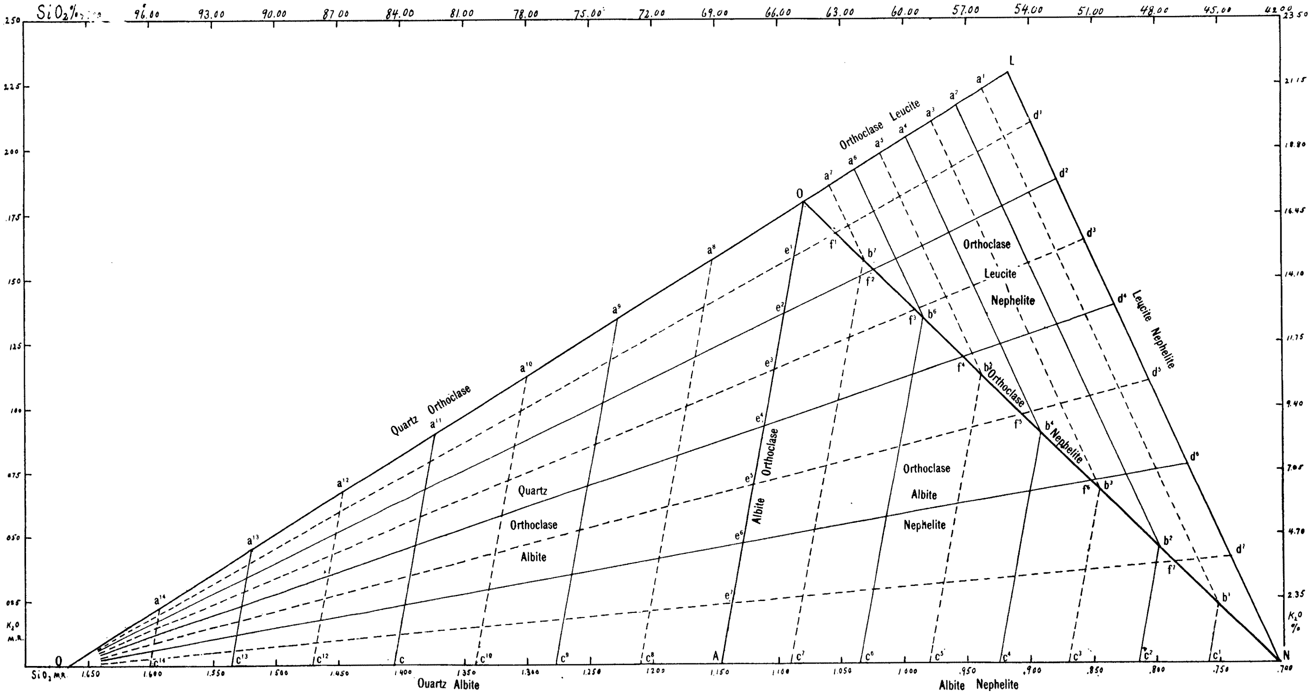
[1] Cf. Michel Lévy, *Bulletin de la Carte géologique de la France*, No. 92 (1903), p. 25.

[2] H. S. Washington, *Professional Paper*, U. S. Geological Survey, No. 14 (1903), pp. 84–87.

[3] J. P. Iddings, *Journal of Geology*, Vol. VI (1898), Plates IX and X; and *Professional Paper*, U. S. Geological Survey, No. 18 (1903), Plate II.

Plate I


SiO2 %
96.00
93.00
90.00
87.00
84.00
81.00
78.00
75.00
72.00
69.00
66.00
63.00
60.00
57.00
54.00
51.00
48.00
45.00
42.00
23.50
21.15
18.80
16.45
14.10
11.75
9.40
7.05
4.70
2.35
K2O %
.250
.225
.200
.175
.150
.125
.100
.075
.050
.025
K2O M.R.
SiO2 M.R.
1.650
1.600
1.550
1.500
1.450
1.400
1.350
1.300
1.250
1.200
1.150
1.100
1.050
1.000
.950
.900
.850
.800
.750
.700
Quartz Albite
Albite Nephelite
Quartz Orthoclase
Orthoclase Leucite
Leucite Nephelite
Orthoclase Nephelite
Albite Orthoclase
Orthoclase Leucite Nephelite
Orthoclase Albite Nephelite
Quartz Orthoclase Albite
Q
O
L
N
A
a1
a2
a3
a4
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a6
a7
a8
a9
a10
a11
a12
a13
a14
b1
b2
b3
b4
b5
b6
b7
c
c1
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c10
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c14
d1
d2
d3
d4
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d6
d7
e1
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e3
e4
e5
e6
e7
f1
f2
f3
f4
f5
f6
f7

quently obtains curves instead of straight lines. Furthermore, Iddings' first diagrams were constructed before the elaboration of the magmatic divisions of the quantitative system, so that the center-points and border-points of these are not considered, while in his later diagram the limits are given for the orders and rangs of potash-lime and soda-lime rocks, the alkalies being considered separately.

It may be pointed out that all such diagrams represent loci of chemical equilibrium, the lines or curves being those of definite combinations of the chemical or mineral constituents. They are analogous to the pressure-temperature, concentration-temperature, and other diagrams employed to represent physico-chemical equilibria. It may also be noted that, apart from considerations of simplicity, convenience, or intelligibility, it makes no difference whether ratios or percentages are chosen as bases for plotting. The relations will be evident in either case.

Turning to Plate I, the line LN is the locus of norms composed wholly of leucite and nephelite, passing through the center-points of the various subrangs of order 9 in a persalic and peralkalic magma. Pure leucite is found at L and pure nephelite at N. Between these extremes are varying mixtures of the two, the points for definite combinations, which correspond to the center-points and border-points of the subrangs, being indicated by the intersections with the solid and broken lines which slope down toward the left. To the right of or above this line no peralkalic and persalic norms can exist, since there will be insufficient silica to satisfy the alkalies unless kaliophilite is formed, and this molecule has been excluded from consideration. To the left of or below it there will be an excess of silica, so that either orthoclase or albite or both will be present.

The line OA is the locus of purely feldspathic norms, that is of the center-points of order 5, composed wholly of orthoclase and albite in varying proportions, pure orthoclase being found at O and pure albite at A, and the definite combinations which correspond to the center-points and border-points of the subrangs being indicated by the intersections with the solid and broken lines which extend upward toward the right. To the right of this line the norms must contain nephelite or leucite, or both of these, the maximum amounts being reached at the leucite-nephelite line LN, along which lenads alone are found. To the left of the orthoclase-albite line OA there is an excess of silica over that needed for the feldspars, so that the norms must contain quartz.

Connecting O and L is the line LO, which is the locus of purely potassic norms (the ordinal center-points of subrang 1), consisting of varying amounts of orthoclase and leucite, from pure orthoclase at O to pure leucite at L. Below this line soda is present, forming either albite or nephelite, or both, while above it no norms can exist, for the reason to be mentioned presently.

Although irrelevant to the immediate discussion, the line OQ may be mentioned. This is continuous with LO, and is the locus of norms composed only of orthoclase and quartz in varying proportions, orthoclase occurring at O and quartz at Q. Above and to the left of this orthoclase-quartz line, as well as its continuation OL mentioned above, no norms can exist, since, for any given point in this region, the sum of the silica, alumina, and potash will be greater than 100 per cent if alumina and potash remain equal, or, if the necessary alumina is excluded, the potassium metasilicate molecule will be present, and this we have excluded from consideration. To the right of and below this line the norms will contain increasing and varying amounts of albite and nephelite, and decreasing amounts of quartz, until the orthoclase-albite line OA is reached, when quartz vanishes and to the right of which nephelite enters into the norm.

Within the area LOAN, therefore, are to be found all norms composed only of orthoclase, albite, leucite, and nephelite. The purely potassic ones will lie along the leucite-orthoclase line LO, and those richest in leucite toward the top of the area around the point L, while the purely sodic ones will be found along the albite-nephelite line AN, the albitic ones being around the point A. As albite and leucite cannot coexist in the norm, *ex hypothese*, it is clear that in one part of the area LOAN leucite must be present without albite, while in another part albite will be present without leucite, in each case in combination with varying amounts of orthoclase and nephelite.

The line separating these two is the line ON, which is the locus of norms composed only of orthoclase and nephelite in varying amounts, from pure orthoclase at O to pure nephelite at N. To the left of this the norms contain orthoclase, albite, and nephelite, but no leucite; while to the right of it they contain orthoclase, leucite, and nephelite, but no albite.

This orthoclase-nephelite line ON is therefore a highly important one in our discussion, marking, as it does, one limit of leucitic norms, the others being the leucite-nephelite and leucite-orthoclase lines LN and LO, beyond which no norms can exist, as we have seen above. Within the leucite-orthoclase-nephelite area LON, therefore, must fall all leucitic peralkalic and persalic norms, and this may be called the *leucitic area.* Several features of this leucitic area deserve remark as bearing on the subsequent discussion. The first is the small size as compared with the feldspar-nephelite area OAN and the feldspar-quartz area OQA. Calling the area of the leucitic area of LON unity, that of OAN is 1.662, and that of OQA is 1.966. Or expressed in percentages of the whole area LQN they are as follows: LON = 21.61, OAN = 35.91, and OQN = 42.48.

The second feature is the shape and the position of the leucitic area—an acute-angled, almost isosceles, triangle, with the apex down and inclined sharply to the right. In consequence of this shape and position, the greatest variation in potash occurs at the silica percentage of leucite, $S = 0.9194$, and the greatest variation in silica at the potash percentage of orthoclase, $K = 0.180$. Therefore, as the percentage of silica of the magma falls below that of leucite, the possible range in potash rapidly diminishes till the silica percentage of nephelite is reached at $S = 0.704$, while as the percentage of silica of the magma rises above that of leucite the range in potash diminishes at a more rapid rate until the silica percentage of orthoclase is reached, above which no leucite can exist.

Crossing the whole area LQN are seen two sets of lines, one representing the loci of the center-points and border-points of the orders, and the others the center-points and border-points of the subrangs. The lines $a^1b^1c^1$, $a^2b^2c^2$, etc., are the loci of the different ratios of lenad to feldspar and of feldspar to quartz, corresponding to the center-points and border-points of the orders. The ordinal lines $a^1b^1c^1$ to $a^7b^7c^7$ are broken at the intersections b^1, b^2, etc., with the orthoclase-nephelite line ON, the lower limiting value of the leucitic area, while a^9c^9 to $a^{16}c^{16}$ are straight and continuous. This change in direction or refraction in passing out of the leucitic area follows mathematically from the change in the norm. Starting from the top, where the magmas are perpotassic, increase in soda necessitates an increase in the amount of nephelite, this being the only sodic mineral present, and orthoclase being the only feldspar possible within the leucitic area. This brings about a decided decrease in the silica percentage, as that of nephelite is much less (42.25) than those of orthoclase (64.75) and leucite (55.05). On the other hand, left of the orthoclase-nephelite line ON, where the potash enters only into orthoclase and the relative amount of nephelite remains constant along the ordinal line, increase in soda necessitates an increase in the amount of albite. This causes a rise in the silica percentage, since that of albite (68.70) is higher than that of orthoclase (64.75).

The other set of lines, $d^1f^1e^1Q$, $d^2f^2e^2Q$, etc. are the loci of different ratios of potash to soda, corresponding to the border-points and center-points of subrangs. Since along these subrang lines the relation of potash to soda remains constant and the variation is in the amount of silica, an increase in silica causes an absolute decrease in the amount of potash, expressed by a slope of the line to the left. They are therefore straight and continuous, vanishing at the left in the point Q, which is the locus of pure quartz.

A study of the sizes and forms of the various areas included between the dotted lines corresponding to the limits of the various magmatic divisions of persalane (except the rangs, those here represented being all peralkalic) is of interest as showing the differences between these and their possible normative characters in different directions. But this is apart from our subject, and would lead us too far astray.

We have been dealing so far only with persalic and peralkalic magmas, in which only quartz, orthoclase, albite, leucite, and nephelite can form. But it is well known that such rocks are extremely rare, plagioclase feldspars and femic minerals entering into the norms of nearly all igneous rocks to a greater or less extent. To render our theoretical data adequately comparable with actual rocks, therefore, we must consider magmas which contain salic lime, and an equal amount of alumina, furnishing anorthite, and those which contain femic molecules, in both cases with varying amounts of silica and alkalies. It is clear that it would be a very complicated undertaking to examine these fully, owing to the many combinations possible and the almost unlimited number of choices in the matter of variables, especially when the femic minerals are considered. But fortunately the calculation and presentation of a large number of hypothetical magmas is not necessary, and the general principles can be readily shown by a few typical cases.

Still adhering to persalanes, we may introduce anorthite and examine domalkalic and alkalicalcic magmas, that is, those in which the total alkalies are respectively, three times the amount of lime, and equal to it, corresponding to the center-points of the second and third rangs. The norms of these would contain quartz, orthoclase, albite, anorthite, leucite, and nephelite, in all possible combinations and amounts, except that albite and leucite would never occur together. These are represented on Plate II.

In Plate II the black lines represent the loci of persalic magmas, the green those of dosalic magmas, and the red those of salfemic ones. The orthoclase-quartz line OQ, and the feldspar-quartz area OQA, have been omitted as irrelevant to the discussion, but it is to be remembered that these quaric areas are always to be understood as existing, even though unrepresented. Also the lines which express the relations of feldspar to lenad (orders) and of potash to soda (subrangs) are omitted, as their presence would complicate the diagram with little compensating advantage. The dotted lines A^1L^1 and L^1M will be referred to subsequently. The small squares and circles represent the positions of actual rocks, and will be referred to subsequently. In the pages which follow, letters in italics, as *LON* for instance, indicate homologous points, lines, and areas in general, without specification of any particular kind of magma.

The solid black lines, marked L^1, O^1, etc., are the loci of persalic and *peralkalic* magmas, which have been treated above, and these are identical with the corresponding ones on Plate I. The black lines made up of long dashes, and marked L^2, O^2, etc., are the loci of persalic and *domalkalic* magmas; while those composed of short dashes, and marked L^3, O^3, etc., belong to persalic and *alkalicalcic* magmas.

Comparison of these three systems reveals some interesting relationships. The leucite-nephelite lines L^1N^1, L^2N^2, etc., and the orthoclase-nephelite lines O^1N^1, O^2N^2, etc., are very close together and parallel, this being due to the fact that in nephelite and in anorthite the relative number of molecules of silica to those of soda and of lime is the same in both(2 : 1),while the molecular weights of soda and of lime (62 and 56), and consequently of nephelite and of anorthite (284 and 278), are approximately the same. These lines, however, shift successively to the left or more siliceous end of the diagram with the introduction of the anorthite molecule, since the silica percentage of this is slightly higher than that of nephelite, 43.17 and 42.25 respectively.

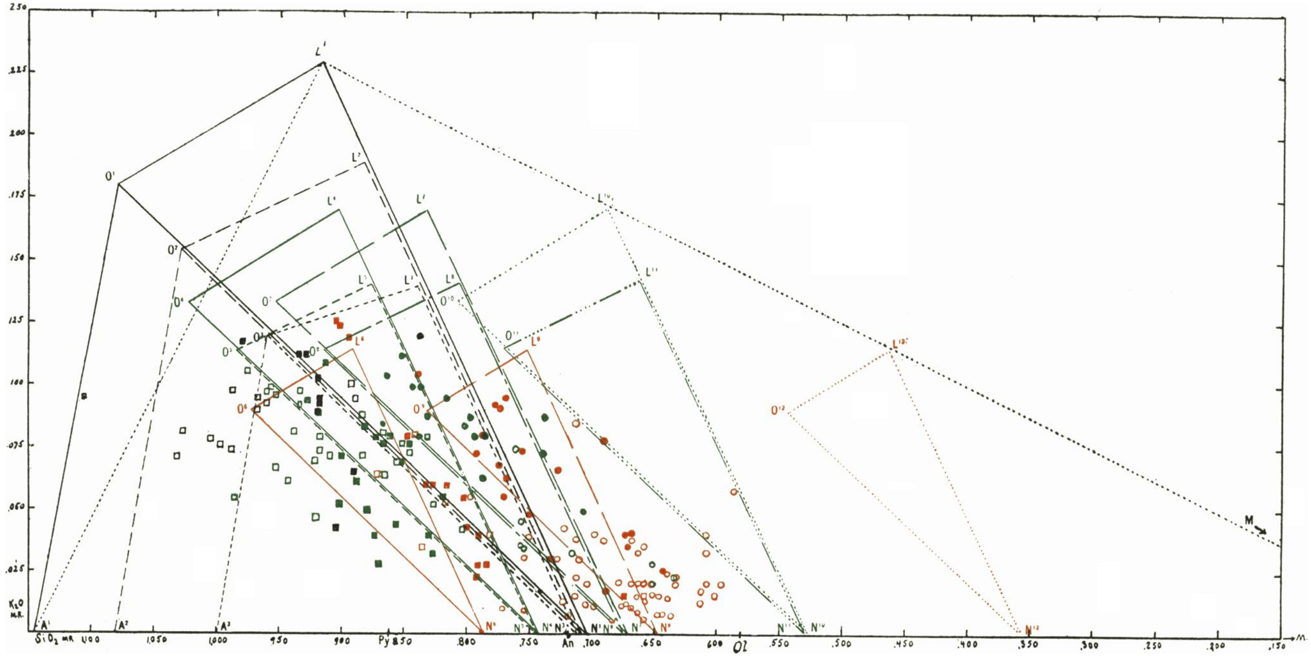
On the other hand, the introduction of the anorthite molecule reduces the amount of potash present, so that the lines L^2O^2 and L^3O^3 are successively lower than the peralkalic line L^1O^1. They are also shifted successively toward the right or less siliceous end, owing to the low percentage of silica in anorthite. L^2O^2 and L^3O^3 are not parallel to L^1O^1, since they are continuous with the lines O^2Q and O^3Q, not shown in the diagram, these perpotassic borders ending in the common point Q. It will also be seen that the lines O^2A^2 and O^3A^3 are successively lower and more to the right than O^1A^1, this following from the considerations mentioned above.

It will also be of interest to examine the relative sizes of the various areas, the quaric areas *OQA* being also considered, as of possible interest, though not pertinent to the present discussion. The size relations are shown in the two succeeding tables, the first showing the relative sizes referred to the corresponding peralkalic area as unity, and the second in percentages of the whole area LQN.

It will be seen that, while the leucitic areas become successively smaller with increasing lime, yet that relatively to the feldspathic areas, *OAN*, they remain practically constant; this last relationship being due to the very slight shift in the diagram toward the left of the lines *LN* and *ON*. It will also be seen that, as lime enters, the leucitic area decreases, as does the feldspathic area, but that the quaric area increases, relatively to the whole amount of possible magmas.

All the above relations will, of course, be the same in direction, though differing in amount, if the magma is assumed to be docalcic, while if it be percalcic the areas will vanish in the point $SiO_2 =$

Plate II


.250
.225
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K_2O M.R.
SiO_2 M.R. 1.100
1.050
1.000
.950
.900
Py .850
.800
.750
An .700
.650
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Ol
.550
.500
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.350
.300
.250
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M.
L^1
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L^4
L^7
O^4
L^3
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O^7
O^{10}
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L^6
O^{11}
L^9
O^6
O^9
L^{12}
O^{12}
M
A^1
A^2
A^3
N^6
N^3
N^4
N^5
N^1
N^2
N^7
N^9
N^8
N^{11}
N^{10}
N^{12}

TABLE I

RELATIONS OF HOMOLOGOUS AREAS, REFERRED TO THE PERALKALIC AREA AS UNITY

Area	Peralkalic	Domalkalic	Alkalicalcic
LON..............	1.000	0.731	0.417
OAN..............	1.000	0.724	0.434
OQA..............	1.000	0.962	0.855
LQN..............	1.000	0.827	0.609

TABLE II

RELATIONS OF HOMOLOGOUS AREAS, IN PERCENTAGES OF THE AREA *LQN*

Area	Peralkalic	Domalkalic	Alkalicalcic
LON..............	21.61	19.11	14.78
OAN..............	35.91	31.45	25.60
OQN..............	42.48	49.44	59.62
LQN..............	100.00	100.00	100.00

0.719, along the abscissal axis, this being the molecular amount of silica in anorthite. This is also the point of intersection of lines drawn through L^1, L^2, etc., and through O^1, O^2, etc., with the line QN. Consequently all persalic leucitic norms will lie in the area $L^1O^1An\ N^1$.

From the above we may draw the following conclusions as to the influence upon the leucitic area of the introduction of anorthite into the magma. The possible range in potash for any magma with a percentage of silica greater than that of the corresponding mixture of leucite and anorthite will be decreased, while for silica percentages below this point there will be but little change. For homologous magmas, as regards order and subrang, the absolute amount of potash will decrease, while that of silica will also decrease down to a certain point, dependent on the magma, after which it will slowly rise.[1] As the amount of anorthite increases, the size of the leucitic area decreases, both absolutely and relatively to that of the whole area of possible norms, this decrease being increasingly great.

It is therefore clear that, in general, the introduction of anorthite into persalic magmas has little influence on the presence of leucite in the norm, except when they are highly potassic, or unless the amount of salic lime exceeds that of the alkalies, when its influence will be increasingly felt.

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[1] Compare the figures on p. 95 of *Professional Paper* No. 14, U. S. Geological Survey, 1903. Those for the more lenic orders are incomplete, as the compositions of the more calcic rangs of these, which cannot exist according to the definition of the respective orders, were not calculated.

We may now introduce femic molecules into the magma and see what influence they exert upon the presence of leucite. In order not to complicate the calculations unduly, we shall examine only a few simple, but typical, cases.

Let us first assume that the femic mineral is a standard, non-aluminous pyroxene exactly intermediate between diopside and hedenbergite—with $MgO = FeO$, and the formula $Ca\,(Mg, Fe)(SiO_3)_2$. The molecular weight of this is 232, and its silica percentage is 51.72, intermediate between that of orthoclase and those of nephelite and anorthite. We shall also assume that the magmas are centrally dosalic and salfemic—that is, with the amount of salic minerals in the norm three times that of the femic, and equal to it respectively. In the case of the dosalanes we may also consider the two cases in which the magma is either peralkalic or domalkalic. The variable factors then will be the relations of feldspar to lenads and of potash to soda, as in the previous cases. The lines which limit the leucitic areas in these norms are shown in Plate II, the peralkalic and domalkalic dosalanes respectively by solid and short-dashed green lines, and the salfemic magmas by solid red lines. The orthoclase-albite lines (*OA*) are omitted, as unnecessarily complicating the diagram. They may be drawn in, if desired, from the points *O* to *A*, parallel to the lines O^1A^1, O^2A^2, and O^3A^3.

Confining our attention, therefore, to the leucitic areas alone, it is evident that these are all identical in shape with those of the persalanes which are homologous as regards salic lime. The lines L^4N^4, L^5N^5, and L^6N^6 are parallel to L^1N^1, L^2N^2, and L^3N^3, and similarly the lines *ON* are all parallel to each other. On the other hand, the peralkalic L^4O^4 and L^6O^6 are parallel to the peralkalic L^1O^1, while the domalkalic L^5O^5 is parallel to the domalkalic L^2O^2.

With increasing amounts of pyroxene, the several leucitic areas become smaller, until they would vanish (for peralkalic magmas) in the pure assumed pyroxene at the point Py, where $SiO_2 = 0.862$ on the line QN, which is also the intersection point of lines drawn through the homologous points L^1, L^4, and L^6, and O^1, O^4, and O^6. Furthermore, the areas are shifted successively toward the more siliceous end of the diagram, owing to the higher percentage of the pyroxene in silica than in nephelite, It will also be noted that the influence of the introduction of anorthite is exactly similar in character to that already noted in the case of the persalanes, though the change is less quantitatively, as shown by the lines L^4N^4 and L^5N^5, and O^4N^4 and O^5N^5, being closer together than was the case with the homologous lines in the persalanes. But it seems needless to go into greater details, as the principles will be the same as with the preceding cases.

We may next assume that the femic molecule is an olivine, exactly intermediate between forsterite and fayalite—that is, with $MgO = FeO$. The molecular weight of this is 172, and the silica percentage is 35.88. As in the preceding case, we shall consider both dosalic and salfemic magmas, and in the former shall assume the magmas to be peralkalic and domalkalic, while in the salfemanes only peralkalic ones will be considered. Pyroxene is assumed to be absent in all these cases.

The leucitic areas of these various olivinic magmas are shown in Plate II, the peralkalic and domalkalic dosalanes respectively by green lines made up of very long dashes and of the same with alternating short ones, while the salfemic magmas are represented by red lines made up of very long dashes. Here again the triangular leucitic areas are of exactly the same form and parallel to the homologous ones in the persalanes and the pyroxenic magmas, and, furthermore, the sizes of the olivinic areas are the same as those of the corresponding pyroxenic ones. Thus, $L^7O^7N^7$is the same size as $L^4O^4N^4$, and $L^9O^9N^9$ as $L^6O^6N^6$, and so on. This, of course, is due to the fact that the relative amounts of potash in homologous magmas remains the same whether olivine or pyroxene is introduced. But it will be seen that the introduction of olivine, rather than pyroxene, shifts all these leucitic areas well toward the right, or less siliceous, end of the diagram, a consequence of the lower silica percentage of the olivine. Furthermore, as in the preceding cases, increase in the amount of olivine lessens the size of the triangle until, for perfemic magmas, they would vanish at the point Ol, where $SiO_2 = 0.598$ in the line QN, which is the locus of our assumed olivine, and which is also the intersection of lines passing through L^1, L^7, and L^9, and through O^1, O^7 and O^9. Here also the influence of the introduction of anorthite is similar to that observed in the preceding cases, in the olivinic as in the pyroxenic salfemanes the lines LN and ON respectively falling so close together, in the otherwise homologous cases, as to be indistinguishable unless the diagram is drawn on a much larger scale than that used here.

Finally, we may introduce molecules of magnetite (without either pyroxene or olivine) into peralkalic and domalkalic dosalanes and peralkalic salfemanes. The leucitic areas of these are shown respectively by green lines made up of dots, and of dots and short dashes, and by red lines made up of dots. Here the shift toward the right or less siliceous end of the diagram is very pronounced, owing to the entire absence of silica from the femic mineral.[1] But the triangles are of exactly the same sizes as in the homologous cases just studied, and the homologous lines are all parallel. Furthermore, the leucitic areas become smaller and smaller absolutely with increase in magnetite, until they vanish at the point M, where $SiO_2 = 0$, the locus of non-siliceous magmas, which lies to the right and outside of the diagram.

In the preceding cases we have assumed magmas of definite compositions, corresponding to certain center-points in the quantitative classification, as well as femic mineral molecules of simple and definite compositions and introduced singly. But it is clear that greater or less admixtures of anorthite or of femic molecules, or the introduction of several femic molecules simultaneously, will influence the positions of the various loci to a greater or less extent, but always in directions similar to those indicated by the examples given. Thus, if pyroxene and olivine, or pyroxene and magnetite, or all three, were assumed to be present in different proportions, the positions of the corresponding leucitic areas would lie between those of purely pyroxenic and purely olivinic or magnetitic ones, corresponding to the salic content, the exact position depending on the relative amounts and the compositions of the minerals present.

But in all cases—and this point is of great importance in the subsequent discussion when we come to deal with actual rocks—homologous lines would be parallel to each other. Thus, the lines *LN* would be parallel to those here given, as would be the lines *ON* parallel to the lines *ON* of the diagram. It follows from this that the acute angle *LNO* of all possible leucitic areas would be the same, and also that the angles *LNM*[1] and *ONQ* would also be constant, so that the inclination of the triangular leucitic areas as regards the abscissal line QM would always be the same.

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[1] Apatite, ilmenite, corundum, or any other non-siliceous mineral would have, of course, the same effect as magnetite.

On the assumption that the kaliophilite molecule is excluded, it is also evident that all possible rock magmas must fall within the large triangle L^1QM, since outside of and above it there will be too much potash, as explained on a previous page (p. 272), and the points Q and M respectively represent pure quartz, or 100 per cent of silica, and pure non-siliceous mineral, or 0 per cent of silica.

As regards the sizes of the various leucitic areas, it is clear that, while they decrease absolutely with increase in anorthite or femic molecules, yet that relatively to the areas *OAM*, *OQA*, *LQN*, *LNM*, and *LQM*, corresponding in the relative amount of anorthite in any given case, they remain constant. This follows geometrically from the parallelism of the sides of the various homologous areas. Thus the ratio of the size of the salfemic and magnetitic leucitic area $L^{12}O^{12}N^{12}$ to the whole area $L^{12}Q^{12}N^{12}$ is the same as that of the persalic leucitic area $L^1O^1N^1$ to the whole area $L^1Q^1N^1$, since their homologous sides are parallel.

In general, therefore, the influence of the presence of anorthite and of standard, non-aluminous pyroxenes is to lower the percentage of potash without greatly disturbing the percentage of silica, or, in other words, to raise the ratio of silica to potash for the leucitic areas; while the presence of olivine molecules tends to lower this ratio to a less extent, the change being nil in the case of magnetite, and also to diminish to a much greater degree the percentage of silica in the magma, this reaching a maximum with magnetite.

In consequence of these relations, and those discussed in the preceding paragraphs, while with increase in femic minerals the leucitic areas extend on the whole toward the non-siliceous end of the diagram, so that eventually they cover the whole area to the right of the line O^1N^1, yet for any given set of magmas, homologous as regards the relative amounts of anorthite and given femic minerals, and variable only as regards feldspars and lenads and soda and potash, and consequently with fixed limits (*LQN*) for all possible magmas, there will be no disturbance of the ratios of the normatively leucitic ones and those normatively free from leucite.

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[1] M is used to indicate the locus of magnetite where $SiO_2=0$ and $K_2O=0$, as explained above.

From the above discussion and study of the diagrams, and on the assumption that potash has a greater affinity for silica than has soda or any other of the bases, we may draw the following conclusions as to the relations between the chemical composition of the magma and the formation of leucite, which are to be tested later by comparison with the data furnished by actual rocks.

1. There should be no leucitic rocks with an excess of silica over that necessary to bring all the bases to their highest silicated condition —that is, leucite should not occur in rocks whose norms show the presence of normative quartz.

1*a*). As a corollary to this we should never expect to find modally leucitic rocks with a silica percentage greater than 64.75, that of orthoclase; and as femic minerals and anorthite enter into the magma, the silica percentage of possible leucitic rocks should never exceed that of a mixture of orthoclase with the appropriate amounts of anorthite and femic minerals.

2. On the other hand, we can expect to find leucitic rocks with silica percentages running down to zero as a limiting value.

3. We should expect to find the greatest range in the percentage of potash consistent with the presence of leucite, and consequently the greatest number of leucitic rocks, with silica percentages about equal to those of mixtures of leucite and the appropriate amounts of anorthite and femic minerals. From these maxima the range in potash and the number of leucitic rocks should diminish slowly as silica falls, and should diminish more rapidly as silica rises.

4. We should not expect to find rocks without normative leucite carrying this mineral in the mode, and conversely we should expect rocks with normative leucite to carry this mineral modally.

4*a*). As a corollary to this it follows that, if the locus of a rock, expressed in terms of the percentages of silica and potash, and plotted as on Plate II, falls within the leucitic area corresponding to its characters as regards anorthite and femic minerals, it should have leucite in the mode; while, if it falls outside of this area, it should be modally free from this mineral.

5. From the relative sizes of the leucitic and non-leucitic areas we should expect leucitic rocks to be much less abundant than non-leucitic ones.

6. We should not expect the presence of femic molecules in the magma to exert much influence on the presence of leucite, while the presence of anorthite should tend to lessen the probability of its presence, this influence being increasingly felt as the magma becomes more calcic.

Consequently we could expect to find leucitic rocks with very large amounts of femic molecules, but should not expect to find them with large amounts of salic lime, that is, when the amount of this exceeds that of the alkalies.

7. Other things being equal, there should be more probability of a rock being leucitic the higher the potash, while with increase in soda as regards potash the tendency toward the formation of leucite should diminish rapidly, so that we should not expect to find many leucitic rocks with soda in excess of potash.

There are given on Plate III the results of the data for persalic and peralkalic magmas plotted with the abscissas representing percentages of silica (but with 100 per cent to the right), and with the ordinates representing the ratios $\frac{SiO_2}{K_2O}$. Otherwise it is analogous to the diagram on Plate I. It is introduced because it is explanatory of my previous study of the subject, where this method of plotting was adopted, and because it is illustrative of the complexity introduced by the adoption of ratios rather than percentages as a basis for plotting, while the general relationships are still manifest. A brief description must suffice.

The lettering, and the signification of the lines and areas, on Plate III are the same as on Plate I; only it must be borne in mind that the directions, both up and down and right and left, are reversed, and that non-potassic and purely sodic magmas and normative minerals lie above the diagram at infinity, a serious distortion being thus introduced.

The line LN is that of pure lenad, leucite and nephelite, pure leucite being found at L and pure nephelite where the curve touches its asymptote[1] at infinity and where $SiO_2=0.704$. The line OA is that of pure feldspar, orthoclase being found at O, and albite where the curves become tangent at infinity with its asymptote at $SiO_2=1.145$. The curve LO is that of perpotassic magmas (leucite-orthoclase), and is continuous with the curve OQ, that of quartz and orthoclase, quartz being found at the point where the curve touches its asymptote at infinity and where $SiO_2=1.667$. The curve ON^1 is that of orthoclase and nephelite, orthoclase being found at O and nephelite where the curve touches its asymptote at infinity and where $SiO_2=0.704$, N and N^1 coinciding here.

The leucitic area is therefore bounded by the curves LN, LO, and LN^1, N and N^1 rising and approaching each other with decreasing potash till they coalesce as just explained. The area N^1OA is that of orthoclase-albite-nephelite; and AOQ is that of quartz-orthoclase-albite, both of these extending upward to infinity. The whole area NLOQ, therefore, embraces all possible magmas, since outside of it no norms can exist, as already explained.

The ordinal curves are shown running down the diagram from top to bottom, and with well-marked cusps where they meet the orthoclase-nephelite curve N^1O, the angle of the cusp decreasing as the magma becomes more lenic. This change in direction is due to causes already explained. The curves representing subrangs run across the diagram from left to right. They are all continuous, but become successively steeper with increase in soda, for reasons referred to in a previous page.

Introduction of anorthite and of various femic minerals yield exactly similar homologous curves and areas, which have all been plotted, but which are omitted here. Their influence is quite analogous to that observed on Plate II. Thus the introduction of anorthite causes the curve LO to rise and shift successively toward the left with increasing lime, while the curves NL and N^1O are shifted to the right, but remain very close to each other.

But further description is unnecessary, and it may merely be

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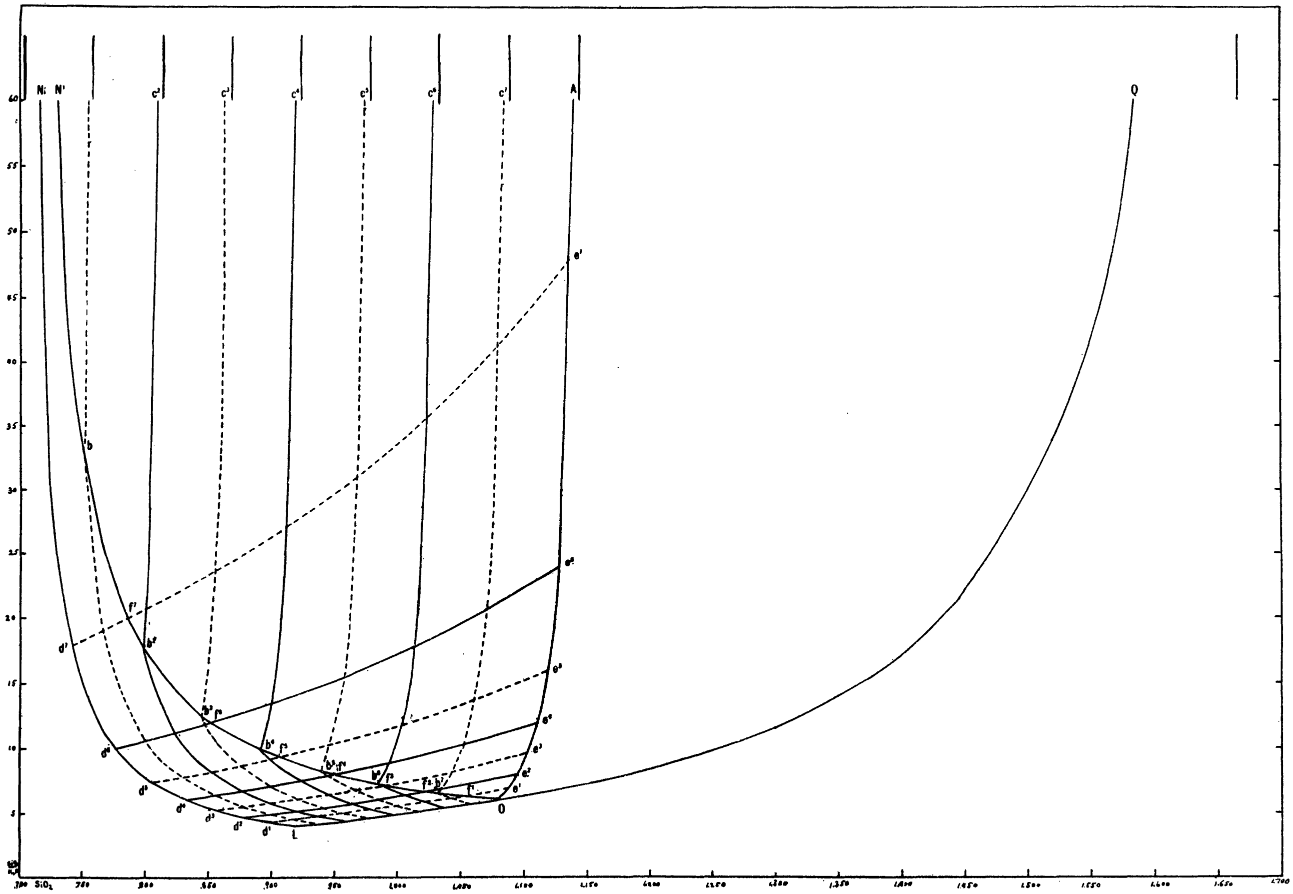
[1] The positions of these fixed asymptotes are indicated by the short straight lines at the top of the diagram.


Ni
N'
c²
c³
c⁴
c⁵
c⁶
c⁷
A
Q
b
e⁷
e⁶
e⁵
e⁴
e³
e²
e¹
f⁷
b²
d⁷
b³
f⁶
b⁴
f⁵
b⁵
f⁴
b⁶
f³
f²
b⁷
f¹
O
d⁶
d⁵
d⁴
d³
d²
d¹
L
60
55
50
45
40
35
30
25
20
15
10
5
700
SiO₂
750
800
850
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950
1000
1050
1100
1150
1200
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1500
1550
1600
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1700

pointed out that all the relations observable on Plates I and II, where the curves resolve themselves into straight lines, are fully manifest on a diagram plotted on this basis, though not so readily intelligible, owing to the distortion introduced.

APPENDIX I

Loci of Leucitic Areas of Various Magmas

No.	Character of Magma	O	L	N	
1....	Peralkalic persalane	1.079 .180	.917 .229	.704 .000	SiO_2 K_2O
2....	Domalkalic persalane	1.028 .154	.883 .189	.708 .000	SiO_2 K_2O
3....	Alkalicalcic persalane	.959 .120	.840 .140	.712 .000	SiO_2 K_2O
4....	Peralkalic dosalane, with diopside	1.025 .135	.904 .172	.744 .000	SiO_2 K_2O
5....	Domalkalic dosalane, with diopside	.986 .116	.877 .142	.746 .000	SiO_2 K_2O
6....	Peralkalic salfemane, with diopside	.971 .090	.890 .115	.783 .000	SiO_2 K_2O
7....	Peralkalic dosalane, with olivine	.955 .116	.833 .142	.673 .000	SiO_2 K_2O
8....	Domalkalic dosalane, with olivine	.916 .116	.807 .142	.676 .000	SiO_2 K_2O
9....	Peralkalic salfemane, with olivine	.830 .090	.749 .115	.643 .000	SiO_2 K_2O
10....	Peralkalic dosalane, with magnetite	.809 .135	.688 .172	.528 .000	SiO_2 K_2O
11....	Domalkalic dosalane, with magnetite	.771 .116	.662 .142	.531 .000	SiO_2 K_2O
12....	Peralkalic salfemane, with magnetite	.540 .090	.459 .115	.352 .000	SiO_2 K_2O

[*To be continued*]